

MAGNET R&D FOR FUTURE COLLIDERS

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Abstract

High-energy colliders complementing and expanding the physics reach of LHC are presently under study in the United States, Europe and Japan. The magnet system is a major cost driver for hadron colliders at the energy frontier, and critical to the successful operation of muon colliders. Under most scenarios, magnet design as well as vacuum and cryogenic systems are complicated by high radiation loads. Magnet R&D programs are underway worldwide to take advantage of new developments in superconducting materials, achieve higher efficiency and simplify fabrication while preserving accelerator-class field quality. A review of recent progress in magnet technology for future colliders is presented, with emphasis on the most innovative design concepts and fabrication techniques.

1 INTRODUCTION

Starting with the invention of the cyclotron by Lawrence, accelerator-based experiments have been the primary source of progress in particle physics. The greatest potential for new discoveries is achieved at the energy frontier. The Fermilab Tevatron, with a collision energy of 2 TeV, is presently the highest energy accelerator in the world. At mid-decade, it will be replaced in this role by the 14 TeV center-of-mass Large Hadron Collider (LHC), presently under construction at CERN. Meanwhile, international studies exploring the physics potential and technical feasibility of next-generation facilities are in progress. The following options have been identified: an electron-positron linear collider that is complementary in physics reach to the LHC; a Muon Collider and a Very Large Hadron Collider (VLHC) that would probe yet higher energy scales. A muon storage ring serving as an intense source of neutrinos is also receiving considerable attention. This machine has a rich physics potential and provides an intermediate step of technology development towards the muon collider.

Due to high cost and long lead times for any facility at the energy frontier, intensive R&D efforts in support of long range planning are needed. Magnet technology is the key enabling technology for VLHC and is critical to the successful operation of a muon collider or neutrino factory. This paper reports recent progress in superconducting magnet R&D for these applications.

Progress in magnet R&D for linear colliders is reported in another paper at this conference [1].

2. MAGNET R&D FOR HADRON COLLIDERS

The concept of a post-LHC hadron collider was first discussed at the 1994 DPF workshop on future hadron facilities. Advances in superconducting materials and the possibility to enhance luminosity taking advantage of synchrotron radiation damping led to a machine design with 30 TeV beam energy and very high field (12.5 T) dipoles [2]. This approach was further explored at Snowmass '96, resulting in the design of a "high-field" Very Large Hadron Collider (VLHC) with center-of-mass energy of 100 TeV and luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Two options were considered, with dipole fields of 9 T or 12 T [3]. At the Snowmass '96 meeting, a "low-field" approach to VLHC based on 2 T superferic magnets was also proposed. In this model, developed at Fermilab in 1996, a low magnet cost per meter and simpler accelerator systems are expected to compensate for the much longer machine circumference [4].

A recent design study has investigated a staged approach to VLHC, based on a 233 km long tunnel [5]. The first stage uses the 2 T superferic magnet and has a center-of-mass energy of 40 TeV at $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity. The second stage uses 10 T dipoles to reach 175 TeV energy (cm) at $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity. Each stage provides a significant step across the energy frontier and holds the promise of exciting new physics. A 300 GeV (cm) electron-positron collider with $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity, or a top quark factory (360 GeV, $10^{33} \text{ cm}^{-2}\text{s}^{-1}$) with affordable power cost are possible in the same tunnel.

Upgrades to existing facilities have also been proposed. For machines built in existing tunnels, magnets operating at the highest possible field are desired. An alternative approach to the staged VLHC can also be envisaged, in which comparable energy scales would be reached with smaller machine perimeter using intermediate field dipoles in the first stage, and very high field dipoles in the second stage.

High gradient quadrupoles are needed in both the arcs and the insertions of high energy hadron colliders. Present LHC requirements are at the limit of NbTi technology. Designs based on Nb₃Sn have been developed at Fermilab, BNL, CEA-Saclay, INFN-Lasa and LBNL for second generation LHC low-beta insertions and next

generation machines. Recent progress in the development of very high gradient quadrupoles is reported in another paper at this conference [6].

2.1 The “Transmission Line” Magnet

Superconducting magnets developed for existing machines show a trend towards better performance at the expense of increased complexity. The low-field VLHC concept represents a radical departure from this trend, aiming at overall cost reduction through drastic magnet simplification. A single turn, 100 kA NbTi transmission line generates the magnetic flux while a warm iron yoke in “double C” configuration shapes the field in two gaps, providing a dipole field in the 0.1-2.0 T range and a superimposed $\pm 4.73\%/cm$ gradient [7].

This approach has significant advantages. An optimal working point is chosen for both field-generating elements. Since the superconducting cable is located in a low-field region at the center of the magnet, and proximity of the conductor to the bore is not critical, operation at high current density (with increased copper fraction) and/or higher temperature than conventional designs is possible. The lower field range allows taking maximum advantage of iron yoke magnetization. A peak operating temperature of 6.5-7 K, warm iron yoke and minimal synchrotron radiation load allow to achieve low refrigeration costs. Combined function design results in the elimination of the arc quadrupoles and longer lattice cells. Together with innovative assembly methods, this allows longer, more cost-effective magnets.

The technical issues associated with the low-field approach have been analyzed in detail by the 2-stage VLHC design study. The estimated cost of the stage-1 magnet system is almost a factor of 3 lower than for SSC (escalated to 2001) and the refrigeration power per TeV of beam energy is down by a factor of 5-10 with respect to other high-energy accelerators. Several drawbacks and challenges have also been identified. Larger machine circumference for a given energy results in higher civil construction costs. Larger machine circumference also results in larger beam stored energy and bigger impact on population and the environment. The choice of a small (20 mm) magnetic gap to limit operating current and yoke size requires careful assessment of beam stability at

injection. Continued magnet R&D is also needed to further reduce field distortions due to iron saturation and address issues of mechanical support of the field-shaping poles and the conductor itself under magnetic forces.

2.2 High Field Magnets

Impressive progress in the performance of A15 and High Temperature superconductors has prompted accelerator designers to investigate machines based on very high field magnets. Nb₃Sn wires now carry currents comparable to SSC-type NbTi strands of the same size at more than twice the field. Further progress in both performance and cost is expected under the DOE sponsored conductor development program [8]. However, all high field superconductors undergo high temperature heat treatment to form the superconducting phase. After reaction, they are brittle and strain sensitive. In order to use them effectively in accelerator magnets, new design concepts and fabrication techniques are needed. Two main paths are being pursued: shell-type and block-type designs.

Shell-type designs

Shell-type coils using keystone Rutherford cable have been adopted in most accelerator applications to date, due to their self-supporting Roman arch structure and optimal use of superconductor in the typical parameter range of interest. However, winding shell-type coils using brittle conductors results in excessive strain and damage to the superconducting filaments. In order to overcome these problems, the coils must be reacted after winding. The Nb₃Sn dipoles MSUT [9] and D20 [10] reached fields of 11-13 T using react-and-wind technology. Large field errors are present in both magnets due to persistent current effects associated with large filament size (40-100 μm) and (in MSUT) eddy current effects due to sintering of strands during reaction and resulting low contact resistance. R&D programs are currently underway at the University of Twente (UT) and Fermilab to develop Nb₃Sn shell-type dipoles which satisfy all accelerator quality requirements.

The goal of the UT program is to fabricate a second generation separation dipole for the LHC Interaction Regions, with large (88 mm) bore and a nominal field of 10 T [11]. The magnet uses new Nb₃Sn Powder-in-Tube (PIT) strand, which achieves high critical current density with small filament size. A 25 μm thick stainless steel core is inserted between cable layers to increase interstrand resistance and suppress coupling currents. Strand fabricated in the early stage of the program showed filament shear fracture after cabling, with significant critical current degradation and contamination of the copper matrix by Sn diffusing from the filaments. Several iterations of strand design and cable fabrication were performed until a cable was developed that meets all demands. The final wire has 20 μm diameter filaments and critical current density of 1.9 kA/mm² (12 T, 4.2 K). Cabling degradation is 5-7%. Mechanical support is

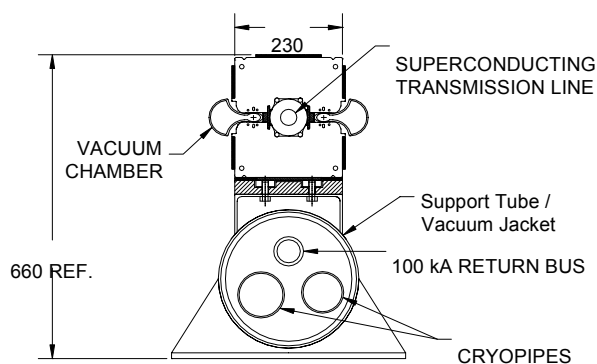


Fig. 1: “Transmission line” magnet cross-section.

provided by stainless steel collars and a 16 mm thick stainless steel shell. Coil fabrication is underway with the goal of testing the magnet at CERN in May 2002.

The shell-type dipole under development at Fermilab, in collaboration with KEK and LBNL, for use in VLHC has 43.5 mm aperture and a nominal field of 11 T. The magnet uses Modified Jelly Roll (MJR) strand [12] which can achieve critical current density well above 2 kA/mm^2 (12 T, 4.2 K) but is presently limited to filament size of the order of $100 \mu\text{m}$. Correction schemes based on thin iron strips placed on the beam tube or inside the superconducting cable are used to control magnetization harmonics [13]. Such passive correction schemes do not address dynamic effects (persistent current decay and snap-back) but are well matched to VLHC scenarios allowing single turn injection. The first model magnet has been fabricated [14] and is presently being tested. It has a single bore and a cold iron yoke. Each coil has two layers wound from one length of cable. Coil mechanical support is provided by a vertically split yoke locked by aluminum clamps and stainless steel skin. Design studies for twin aperture magnets with both warm and cold iron yoke have also been performed [15].

Block-type designs

Despite the remarkable progress in fabricating shell-type coils with brittle superconductors, some basic limitations can be identified. As the field magnitude increases, it is necessary to reduce the magnet aperture in order to limit stored energy, conductor volume and Lorentz forces. From the beam physics standpoint, a reduction of magnet aperture is allowed by smaller beam size at higher energy. Synchrotron radiation absorbers placed between magnets may allow substantial reduction of beam screen cooling requirements and size of the cooling channels [16]. As field increases and magnet aperture decreases, the advantages of shell-type coils are progressively lost. Since cable keystoneing is limited by degradation at the narrow edge, a larger fraction of the coil area is allocated to wedges, decreasing the magnetic efficiency. Winding issues become critical due to tight bending radii at the poles. Azimuthal force accumulation results in high stress levels at the magnetic midplane.

These considerations, along with the need for design simplification and cost reduction, have led several groups to reinvestigate block-type geometries. The “common coil” concept [17] is particularly well suited to fabrication of two-aperture magnets using brittle conductor. A pair of racetrack coils is shared by both apertures, producing fields in opposite directions. Since the end bending radius is determined by the distance between apertures rather than by bore size, the coils can be wound on larger radii, possibly using pre-reacted cable (react-and-wind) with significant cost saving potential. Flat cables can be fabricated with minimal critical current degradation. In its basic form, the design features a planar coil geometry which simplifies part fabrication and coil winding. However, conductor efficiency and/or field quality

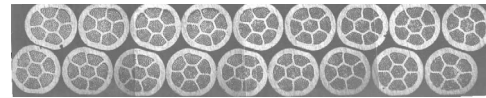


Fig. 2: High current Bi 2212 cable.

requirements may lead to departures from this simple geometry. Disadvantages of the common coil layout with respect to an LHC-type 2-in-1 configuration with shell-type coils are: the need of structural material in the bore to support the coil against horizontal prestress; lack of force redistribution into radial and azimuthal direction, resulting in large horizontal forces; and vertical arrangement of the bores where the return flux from one aperture decreases rather than enhancing the field in the other. Common coil magnet R&D is underway at BNL, Fermilab and LBNL.

The BNL program focuses on the development of react and wind technology with brittle conductors, in particular HTS [18]. A 10-turn coil program was launched to evaluate different approaches to coil fabrication. The reference cable has 30 strands of 0.8 mm diameter, and is wound on an iron bobbin with 70 mm radius using procedures similar to those used in making NbTi coils. Initial tests using Nb_3Sn cable show bending degradation in the range 8%-13%. This is consistent with results obtained by Fermilab, in collaboration with NHMFL and LBNL, by measuring reacted cables subject to strain due to bending and compression in background fields up to 12 T [19]. Fabrication and testing of coils using High Temperature Superconductors (HTS) is also in progress at BNL, in collaboration with Showa, IGC and LBNL. Initial tests of 10-turn coils wound using reacted cable (Fig. 2) have been performed with good results. HTS conductor development shows impressive progress, with new Bi-2212 strand carrying more current than any other wire of similar size at fields above 15 T [20]. However, HTS cost is still a major issue.

The primary goal of the LBNL program is to push accelerator magnet technology towards the highest fields. Following completion of the shell-type dipole D20, which reached 13.5 T at 1.8 K, the R&D effort has shifted to common coil configurations. A series of magnets have been fabricated and tested with increasingly higher fields [21]. The latest dipole in the series, denoted RD3b (Fig.

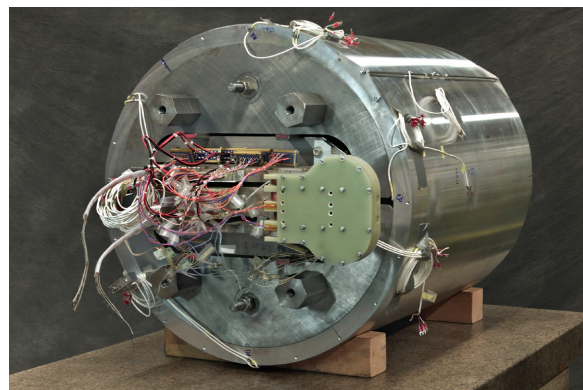


Fig. 3: The RD3b dipole.

3), has surpassed the D20 record reaching 14.6 T at 4.5 K [22]. Among the factors which contributed to this success are availability of state of the art MJR conductor with current density above 2 kA/mm² (12 T, 4.2 K); a design based on coil modules that can be built independently and tested in different configurations; and the use of pressurized bladders to provide warm prestress to the coil pack while tensioning a 40 mm thick aluminum shell [23]. The new support system is successful and accurate in providing very large horizontal prestress and facilitates magnet assembly and disassembly. This last feature is well matched to the modular coil design and allowed quick recovery from a first unsuccessful test of RD3, when an insulation failure occurred resulting in arc damage to the coils. Fabrication of a new inner module (RD3c) is presently underway with the goal of providing geometric field quality at 11 T field level with 40 mm coil spacing. Longer-term plans include fabrication and test of RD4, a 14 T, field quality common coil magnet. Designs suitable for higher field strength are also being explored, taking advantage of further improvements of Nb₃Sn current density to 2.5 kA/mm² (12 T, 4.2 K).

The Fermilab common coil program is developing an 11 T dipole with 40 mm coil spacing for VLHC [24]. In order to reduce the number of parts, inductance and cost, the magnet has a single layer coil with a wide 60-strand cable wound after reaction. Shifted pole blocks and internal spacers allow to obtain good field quality without resorting to auxiliary coils. Due in part to the use of a single layer, a larger portion of conductor is distributed close to the pole region with respect to other designs. Although the pole region is less efficient in generating magnetic field, the resulting geometry has the virtue of compensating magnetization harmonics from different parts of the coil. This results in small persistent current effect even for conductors with large filaments [13]. The coil is supported by strong collars with horizontal bridges, which withstand a large portion of the Lorentz forces and minimize coil displacement during excitation. Since bridges have to be inserted during coil winding, both coils are wound directly inside the collars. An outer stainless steel skin provides horizontal precompression. Fabrication of the first model is underway. At the same time, a react-and-wind coil test is being prepared, using a 41 strand cable and bolted support structure to reach a field of 10 T.

The magnet program at Texas A&M University develops block-coil, single aperture magnets which integrate a high-strength support matrix of Inconel ribs and plates within the coil structure to intercept Lorentz stress and prevent its accumulation on the conductor [25]. Foil springs sandwiched inside each coil block control conductor preload. A first NbTi 7 T model has been built using the same features that will be adopted in the high-field Nb₃Sn dipole. The magnet has been recently tested at LBNL and has successfully reached short sample critical current with minimal training. Fabrication of a 12 T Nb₃Sn dipole is now underway. The design incorporates "mixed-strand" cables with alternating low Cu/Sc

superconducting strands and pure copper strands. Mixed strand cables are being developed at LBNL with promising results [8]. Important cost savings can be realized when protection copper is not included in processing of the Nb₃Sn billets [26].

3 MAGNET R&D FOR MUON COLLIDER AND NEUTRINO FACTORY

Beam energy in electron rings is limited by synchrotron radiation. The concept of a muon collider has been proposed as a means to overcome this limitation and extend the energy reach of lepton machines to the multi-TeV range. Formidable challenges are associated with the design of such facility, in particular due to short lifetime of the muons. Starting in 1994, an intensive R&D effort has been pursued by a collaboration of major high energy physics institutions [27]. More recently, the collaboration has shifted its focus on a muon storage ring to be used as intense source of neutrinos [28]. Both machines critically rely on strong magnets operating under high radiation load. A 20 T solenoid is used to capture pions produced by the proton driver, with 14 T generated by superconducting (Nb₃Sn) coils, and an additional 6 T from a water-cooled insert [29]. Subsequent solenoid channels guide the pions as they decay into muons. High field solenoids (up to 30 T) are required for muon cooling. Beam focusing in the accelerating sections is achieved using special solenoids with bucked coils to completely suppress stray fields in the superconducting cavities. Arrays of dipoles and quadrupoles guide the beam in the arcs of the recirculating linacs, and high field magnets operating under severe radiation load are required for the storage rings. Recent progress in the areas of muon cooling and storage ring magnets is reported.

3.1 Muon cooling

A proposed muon cooling system is based on a sequence of liquid hydrogen absorbers to decrease the muon beam momentum and RF cavities to restore the longitudinal component while the transverse is

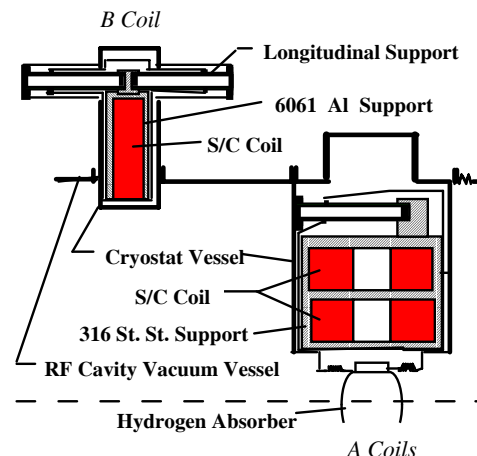


Fig. 4: Muon cooling solenoids

progressively reduced. Focusing is achieved using a solenoid channel with alternating polarity (Fig. 4). In the muon collider, the standard cooling cell has fields up to 30 T in the absorber. Lower fields of 1-6 T are required in the cavity, where flux is reversed. An alternative cooling lattice has field reversal in the absorber. In this case, the highest fields in the channel are lower (16 T vs. 30 T), but flux reversal occurs in the high field magnet and coil support against the large horizontal forces is an issue. The second option is in fact preferred for the neutrino factory due to the larger size of the RF cavity [29].

An experiment has been designed to study RF cavity performance limitations in a solenoidal/gradient field. A 440 mm warm-bore split solenoid with two 250 mm coils separated by a 140 mm gap has been designed at LBNL and fabricated by Wang NMR [30]. It can operate either in solenoid mode with 5 T induction, or in gradient mode with 25 T/m field gradient along the axis. In both cases, the peak field in the coil is close to 7 T. Initial magnet tests showed training due to stick slip motion at the interface between the coil and the aluminum structure supporting the large longitudinal forces. The magnet was commissioned at Fermilab in September 2000. No retraining was observed and the solenoid successfully operated up to 10% above design current in both modes.

3.2 Storage ring

Both muon collider and neutrino factory storage rings achieve optimal performance with minimum arc length. High-field superconducting magnets and maximum lattice packing are thus required. The magnet design is complicated by high radiation loads (up to 1.8 kW per meter in the collider) due primarily to electrons generated by muon decay. Two design approaches have been investigated, using either thick tungsten absorbers placed inside the magnet bore, or split racetrack coils with an open midplane allowing the decay products to be absorbed at higher temperature, away from the coil [31]. A new compact lattice with split racetrack coils is proposed in Design Study II [32]. By partially overlapping top and bottom coils, a combined function design is achieved that eliminates inter-magnet gaps. Short "reverse" coils introduced between main coils enhance the quadrupole field and compensate the large sextupole errors at the coil end. It should be noted that because of shorter beam storing time, field quality requirements are considerably less stringent than in conventional storage rings. The dipoles operate at 7 T. However, due to the large gap at the midplane the peak field is 50% higher thus requiring the use of Nb₃Sn.

4 SUMMARY

Intensive magnet R&D efforts are underway to meet the requirements of future colliders at the energy frontier. New technology and design approaches have resulted in cost-effective VLHC designs which meet accelerator quality requirements. Record dipole fields above 14 T

have been achieved, and further progress to 15-16 T is already possible thanks to impressive improvements in the properties of high field superconductors. Conceptual design of the magnet systems for both Muon Collider and Neutrino Factory has been completed, and experimental work in this area has started.

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